

New Luminous ON Spectra from the Galactic O-Star Spectroscopic Survey

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ABSTRACT

Two new ON supergiant spectra (bringing the total known to seven) and one new ONn giant (total of this class now eight) are presented; they have been discovered by the Galactic O-Star Spectroscopic Survey. These rare objects represent extremes in the mixing of CNO-cycled material to the surfaces of evolved, late-O stars, by uncertain mechanisms in the first category but likely by rotation in the second. The two supergiants are at the hot edge of the class, which is a selection effect from the behavior of defining N III and C III absorption blends, related to the tendency toward emission (Of effect) in the former. An additional

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N/C criterion first proposed by Bisiacchi et al. is discussed as a means to alleviate that effect, and it is relevant to the two new objects. The entire ON supergiant class is discussed; they display a fascinating diversity of detail undoubtedly related to the complexities of their extended atmospheres and winds that are sensitive to small differences in physical parameters, as well as to binary effects in some cases. Serendipitously, we have found significant variability in the spectrum of a little-known hypergiant with normal N, C spectra selected as a comparison for the anomalous objects. In contrast to the supergiants, the ONn spectra are virtual (nitrogen)-carbon copies of one another except for the degrees of line broadening, which emphasizes their probable unique origin and hence amenability to definitive astrophysical interpretation.

Subject headings: stars: abundances – stars: early-type – stars: evolution – stars: fundamental parameters – stars: rotation

1. Introduction

The visibility of material processed by their own interior nuclear reactions at the surfaces of stars is a remarkable diagnostic that will contribute to unique definitions of their evolutionary status and histories, once the complex mechanisms involved can be identified and understood. An inverse N/C,O dichotomy in certain OB spectra was announced and discussed by Walborn (1971, 1976). Unfortunately, reliable quantitative analysis of these spectra has lagged those results by decades, because of the complexity of especially the supergiant atmospheres and winds; only recently have thorough analyses of substantial samples begun to appear (e.g., Rivero González et al. 2011, 2012a,b; Bouret et al. 2012; Martins et al. 2015a,b). There is a growing consensus that the rare extreme cases of the phenomenon bracket systematic trends of nitrogen enrichment among massive stars, such that, e.g., the majority of *morphologically* normal OB supergiants are *physically* enhanced, while the OBC and OBN spectra correspond to opposite extremes, as originally suggested by Walborn (1976). Of course, that can be established only quantitatively, not only because of the range of degrees, but also because morphological detection of even extreme cases depends on the availability of suitable criteria, which is nonuniform and produces selection effects.

The Galactic O-Star Spectroscopic Survey (GOSSS; Maíz Apellániz et al. 2011) ambitiously proposes to observe the blue-violet spectra of every accessible O star in the Galaxy, i.e., a few thousand, with homogeneous resolving power (~ 2500) and signal-to-noise (~ 200). Nearly 450 verified or new classifications have already been published (Sota et al. 2011, 2014; Papers I & II, respectively) and about as many more are in progress. Such a project

is guaranteed to reveal new categories of spectra as well as individual objects of special interest, and that has already occurred (Walborn et al. 2010, 2011). The first of those references addresses curious differences in the relative intensities of N III and C III emission features among Of spectra, which may or may not be related to chemical abundances since selective excitation effects are involved. The second expands upon the ONn category of nitrogen-enhanced, rapidly rotating, late-O giant spectra, further increased by one in this paper. Two new ON supergiants are likewise significant because of their rarity and the need to disentangle possibly multiple physical mechanisms within the category. Thus, these three new objects are presented and discussed in their respective contexts here, along with some related developments in their classification criteria. The new objects will be included in the next installment of the GOSSS classification lists (Maíz Apellániz et al. 2016, in press; Paper III).

2. Observations

Spectroscopic observations of all stars but two discussed here have been obtained with the Boller & Chivens spectrograph attached to the 2.5m du Pont telescope at the Las Campanas Observatory (LCO) in Chile. The Marconi No. 1 2048 × 515 13.5 μ -pixel detector was in use with that instrument. We used a 1200 lines mm⁻¹ grating centered at 4700 Å and had the slit width set to 150 microns, corresponding to 1".26 on the sky and 1.75 pixels on the detector. This instrumental configuration produces a resolution of ~ 1.7 Å as measured from the FWHM of the comparison lines. The typical peak signal-to-noise ratio (S/N) per 2-pixel resolution element ranges from 150 to 200, with just a few cases significantly below or above. Dome flats and bias frames were obtained during the afternoon prior to each observing night as well as twilight flats at sunset, and He-Ne-Ar comparison-lamp exposures were recorded before or after each target was observed. All of these data pertain to the Galactic O-Star Spectroscopic Survey (GOSSS; Maíz Apellániz et al. 2011). They have been adjusted to the uniform survey resolving power of 2500 and are incorporated into the GOSSS database.

HD 191781 and BD +36° 4063 in the northern hemisphere were observed with the Albireo spectrograph at the 1.5m reflector of the Observatorio de Sierra Nevada (OSN), Granada, Spain. The 1800 lines mm⁻¹ grating provided a spectral scale of 0.62 Å per pixel. Further details of these data are given by Sota et al. (2011, 2014).

3. Results

3.1. The ON Supergiants

The blue-violet spectra of the seven ON supergiants are displayed in order of advancing spectral type in Figure 1, together with morphologically normal and OC supergiants below for comparison. Data for these objects are listed in Table 1, in the same order as the figure.

3.1.1. The Spectra of HDE 323110 and 328209

The two new members have somewhat earlier types (higher temperatures), which at first glance had excluded them from the category. That is because the original definition of an ON star required the N III $\lambda\lambda 4634\text{--}4640\text{--}4642$ absorption blend (hereafter “ $\lambda 4640$ ”) to be stronger than C III $\lambda\lambda 4647\text{--}4650\text{--}4652$ (“ $\lambda 4650$ ”), which is not the case in these spectra. However, the other N III features are exceedingly strong, including the $\lambda\lambda 4511\text{--}4515$ blend discussed later as an additional criterion for the class, and especially $\lambda 4097$ in the shortward wing of H δ . C III is also significantly weaker than normal. The relative weakness of $\lambda 4640$ is a result of filling by the Of selective emission, which increases toward earlier types (and higher luminosities), resulting in a strong selection of the ON classification toward the latest O types. We have three observations of HDE 328209, from 2011 March 24, 2013 May 30, and 2014 April 26, among which all spectral features are essentially identical; the second of these is shown in Fig. 1.

The exact spectral types of these two stars are not well defined due to somewhat conflicting criteria. Both the He II $\lambda 4200$ /He I $\lambda 4144$ and He II $\lambda 4541$ /He I $\lambda 4387$ ratios should have values of unity at type O9, increasing toward earlier and decreasing toward later types. However, in both of these spectra the first of those ratios is slightly larger (tending toward type O8.5) while the latter is slightly smaller (type O9.2; Sota et al. 2014). Thus, the compromise type O9 is adopted for both. In the first ratio, the discrepancy is most likely caused by blending with enhanced N III $\lambda\lambda 4196, 4200$. In addition, HDE 323110 is an SB2, with blended, shortward secondary components visible at the He I lines in Fig. 1.

Unfortunately, the luminosity classes of the two spectra are likewise problematic. HDE 323110 appears to have a very weak P Cyg profile at the principal criterion He II $\lambda 4686$, which is consistent with class Ia. (An alternative interpretation could be a blend of lines from the two SB components, weaker in the longward spectrum which would still indicate Ia.) In contrast, in HDE 328209, the $\lambda 4686$ absorption (which weakens with increasing luminosity also due to the Of effect) is only slightly weaker than He I $\lambda 4713$, which calls for class Ib,

Table 1. Observational and Measured Data for the Supergiants

Name	RA	DEC	SpT	V^a	$B - V$	$EW(\lambda\lambda 4511-15)^b$	$EW(\lambda 4650)^{b,c}$	EW Ratio
HDE 323110	17:21:15.79	-37:59:09.6	ON9 Ia	9.67	+1.00	0.44 ± 0.01	0.53 ± 0.01	0.83 ± 0.02
HDE 328209	16:29:19.16	-44:28:14.2	ON9 I	9.77	+0.80	0.74 ± 0.01	0.56 ± 0.01	1.32 ± 0.02
HD 123008	14:07:30.65	-64:28:08.8	ON9.2 Iab	8.84	+0.37	0.62 ± 0.01	0.32 ± 0.01	1.94 ± 0.01
HDE 269896	05:37:49.11	-68:55:01.7	ON9.7 Ia ⁺	11.36	0.00	0.37 ± 0.01	0.29 ± 0.01	1.28 ± 0.02
HD 105056	12:05:49.88	-69:34:23.0	ON9.7 Iae	7.34	-0.14	0.50 ± 0.01	0.36 ± 0.01	1.39 ± 0.02
BD+36°4063	20:25:40.61	+37:22:27.1	ON9.7 Ib	9.69	+0.98	0.40 ± 0.02	0.17 ± 0.01	2.35 ± 0.03
HD 191781	20:09:50.58	+45:24:10.4	ON9.7 Ia	9.53	+0.64	0.44 ± 0.01	0.35 ± 0.01	1.26 ± 0.02
HD 173010	18:43:29.71	-09:19:12.6	O9.7 Ia ⁺	9.22	+0.62	0.51 ± 0.01	1.27 ± 0.01	0.40 ± 0.02
HD 173010			B0 Ia ⁺			0.54 ± 0.01	1.45 ± 0.01	0.37 ± 0.02
HD 104565	12:02:27.79	-58:14:34.4	OC9.7 Iab	9.26	+0.36	0.24 ± 0.01	1.62 ± 0.01	0.15 ± 0.02

^aMultiple photometric sources can be found in SIMBAD, whence the values listed here have been selected. The B magnitude given for HDE 269896 at the top of its SIMBAD page is in error.

^bEquivalent widths and their errors are given in Å.

^cOur measurements of “ $\lambda 4650$ ” necessarily include Si IV $\lambda 4654$, because at our resolution the latter is incipiently resolved from the C III blend only in optimum cases of line quality and weak C III.

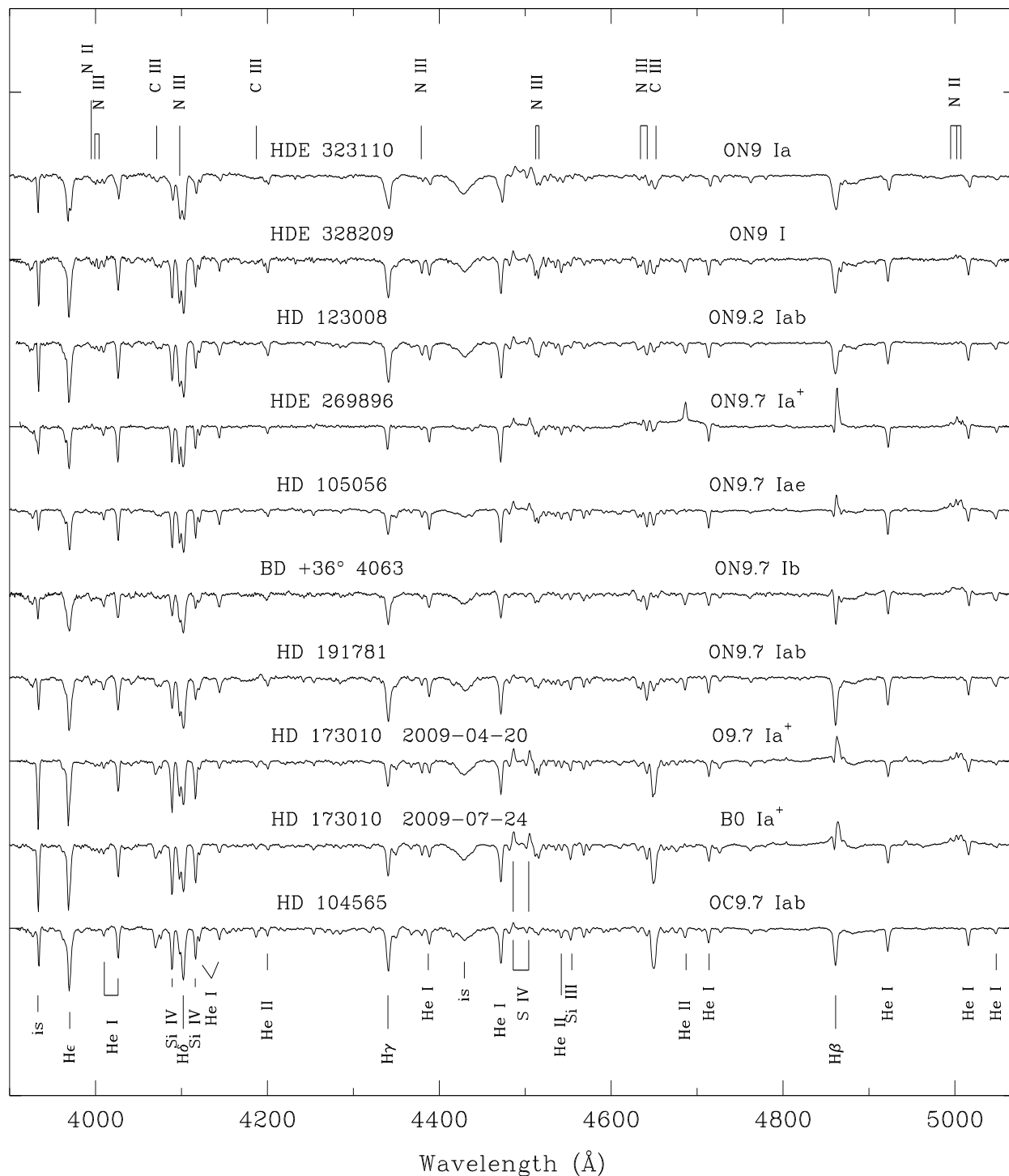


Fig. 1.— The spectra of the known ON supergiants in order of spectral type advancing from top to bottom. Below are plotted examples of morphologically normal and OC spectra for comparison. See Walborn & Howarth (2000, Figs. 3–4) for the wavelengths of the identified spectral features.

in substantial disagreement with the exceedingly strong Si IV $\lambda\lambda 4089, 4116$ absorptions that are appropriate for Ia. Hence, only a relatively indeterminate luminosity class of I can be assigned to this spectrum.

A further interesting feature of these spectra is the prominent quartet of weak, similarly spaced absorption lines near $\lambda 4000$. Its bookends are the usual N II $\lambda 3995$ and He I $\lambda 4009$, which are at the low-ionization extreme of these spectra, while the two intermediate lines, favored by the ionization and nitrogen enhancement, are N III $\lambda\lambda 3999, 4004$ that have similar intensities to the outer two for those reasons. This configuration can be recognized in the other ON I spectra briefly discussed next, albeit with differing relative intensities corresponding to their respective spectral types.

There is also interesting prior and current external information about both of these stars. The anomalous N/C spectra of HDE 323110 (= LSS 4103) were accurately first reported by Vijapurkar & Drilling (1993); our later recognition of this characteristic is independent and thus confirmatory of theirs. Moreover, in agreement with the above description of line profiles in our spectrogram, the OWN Survey (Barbá et al. 2010) has discovered that this object is a short-period, eclipsing, interacting SB2, which will be presented in the context of that program. HDE 328209 was reported to be a runaway star by Moffat et al. (1998) on the basis of HIPPARCOS data.

3.1.2. *Other ON I Stars*

All of the known ON supergiants are included in Fig. 1 for comparison with the two new ones; some of their characteristics are briefly described here. While on the one hand they constitute a homogeneous spectroscopic category, on the other when examined closely they show considerable diversity of detail, and some of them may have diverse physical natures. They are ordered by the He II $\lambda 4541$ /Si III $\lambda 4552$ classification ratio, the unit value of which defines spectral type O9.7, although some range is allowed.

HD 123008 is the earliest/hottest of these spectra, both by that criterion and by the two He II/He I horizontal classification ratios discussed above in the context of the new objects. Actually, those ratios display the same small discrepancy shown by the new members, likely for the same reason, and arguably this spectrum could be classified the same, but it will not be revised here. Martins et al. (2015b) derive $\log(N/H) + 12 = 9.1$ in this spectrum, and $N/C = 61$ by number. The corresponding values in the Sun are 7.9 and 0.25, respectively, as cited by Evans et al. (2004). Some other quantitative results as available will be noted below for comparison.

HDE 269896 is a hypergiant in the Large Magellanic Cloud ($M_V - 8.1$) and displays several remarkable features related to its extreme luminosity that are unique among this set. Most notable is the strong He II $\lambda 4686$ emission line that is very rare at such a late O type. The range of ionizations in emission is also noteworthy, as discussed by Corti et al. (2009), from N II through $H\beta$ to the He II line, probably indicating a very extended atmosphere. It is interesting to note in the present context that $\lambda 4640$ is not stronger than $\lambda 4650$ in this spectrum, either, but that is due to the high luminosity rather than to a higher temperature as in the new members. Evans et al. (2004) quote $\log(N/H) + 12 = 8.3$ and $N/C = 7.9$ for this object, but Corti et al. (2009) found that increasing the former value to 8.9 together with other small parameter changes provides a far better fit to the observed spectrum, including emission vs. absorption features. Sanduleak (Sk) $-66^\circ 169$ also in the LMC has a very similar O9.7 Ia⁺ spectrum except with morphologically normal CNO spectra; for it Evans et al. (2004) derive corresponding values of 7.95 and 4.5, while quoting LMC H II region values of 7.1 and 0.13, respectively, for comparison.

HD 105056 and BD +36° 4063 may be the jokers in this deck. The former is possibly a low-gravity subdwarf, because of its large distance from the Galactic plane, which would be even more extreme if it had a Population I supergiant luminosity (Walborn et al. 1980). The latter is a known SB undergoing active mass transfer (Williams et al. 2009) and its spectrum is significantly variable; HDE 323110 may be a similar system. The unit He II $\lambda 4686$ /He I $\lambda 4713$ ratio in our observation of BD +36° 4063 corresponds to luminosity class II in normal spectra.

HD 191781 lies at the extreme late/cool edge of the O9.7 type, almost but not quite B0. The spectral analysis of Martins et al. (2015b) yields $\log(N/H) + 12 = 8.9$ and $N/C > 15$ in this object.

3.1.3. *Morphologically Normal and OC Supergiants*

HD 173010 is a highly luminous object; the intensities of the Si IV absorption lines are unprecedented, leading to the Ia⁺ classification despite the lack of He II $\lambda 4686$ emission as in HDE 269896. Nevertheless, its C, N spectra are morphologically normal, so it is displayed here as a comparison for the anomalous objects. The N III lines are very strong, except for $\lambda 4640$ which must be filled in. But C III is also extremely strong, cf. $\lambda 4650$. Perhaps this star had a lower initial rotational velocity than those above? The long-unidentified S IV emission lines at $\lambda\lambda 4485, 4503$ (Werner & Rauch 2001) are also extremely strong. One wonders if the metal abundances might be supersolar in this object toward the inner Galaxy.

Surprisingly, we have found that the spectral type and (not independently) the Si ionization of HD 173010 are variable. Two observations are shown in Fig. 1, from 2009 April 20 (upper) and 2009 July 24 (lower). From the He II $\lambda 4541$ /Si III $\lambda 4552$ classification ratio, the first spectral type is O9.7, similarly to the adjacent HD 191781, but the second is substantially later and must be classified as B0 (cf. the atlas of standards in Sota et al. 2011). Concurrently, the Si IV/Si III ionization ratio changes in the same sense, an effect we have not seen previously. Note also the asymmetrical broad emission wings at $H\beta$, as discussed and explained in several B hypergiants and Luminous Blue Variables by Walborn et al. (2015); this profile also appears somewhat variable. Further temporally resolved investigation of this object is underway at high spectral resolution in the OWN survey. Clearly, we still have much to learn about massive stellar atmospheres and evolution.

The OC supergiant HD 104565 is the antithesis of the ON: all the C III features are exceedingly strong, while N III is vanishingly weak for the spectral type. The deficiency of $\lambda 4097$ between Si IV $\lambda 4089$ and $H\delta$ is especially striking and is the hallmark of the class; even in normal spectra it is comparable to the Si IV line. If the initial rotational velocity is a prime cause of mixing, then it must have been extremely low in this star. Martins et al. (2016, in preparation) derive $\log(N/H) + 12 = 8.3$ and $N/C < 1.0$ in this spectrum.

For comparison with the earlier spectral types of the two new ON supergiants, we cite Figure 11 of Sota et al. (2011), which presents a complete luminosity sequence of O9 spectra with morphologically normal CNO. They include α Cam, O9 Ia, for which Martins et al. (2015a) derive $\log(N/H) + 12 = 8.4$ and $N/C = 5$. Then we also call attention to HD 152249, OC9 Iab, in Figure 6 of Sota et al. (2014), for which Martins et al. (2015a) derive corresponding values of 8.1 and 0.46, respectively, again in perfect agreement with the morphological predictions.

3.2. A New ONn Giant

The ONn class of nitrogen-enhanced, rapidly rotating late-O giants was extensively discussed by Walborn et al. (2011), following its augmentation from the GOSSS data. It is remarkably homogeneous, comprising a very small range of spectral types among which the principal variable is the high projected rotational velocity, which in combination with the nitrogen enhancement has striking progressive morphological effects on the $\lambda\lambda 4640\text{--}4650$ blends. The purpose of this section is simply to add a further member to the class, HD 89625, ON9.2 IVn, discovered subsequently by GOSSS. Here it has been incorporated into Figure 2, which is the updated Figure 1 of Walborn et al. (2011). Its location corresponds to its relative $v \sin i$ in ascending order, between HD 150574 ($\sim 200 \text{ km s}^{-1}$) and HD 13268/91651

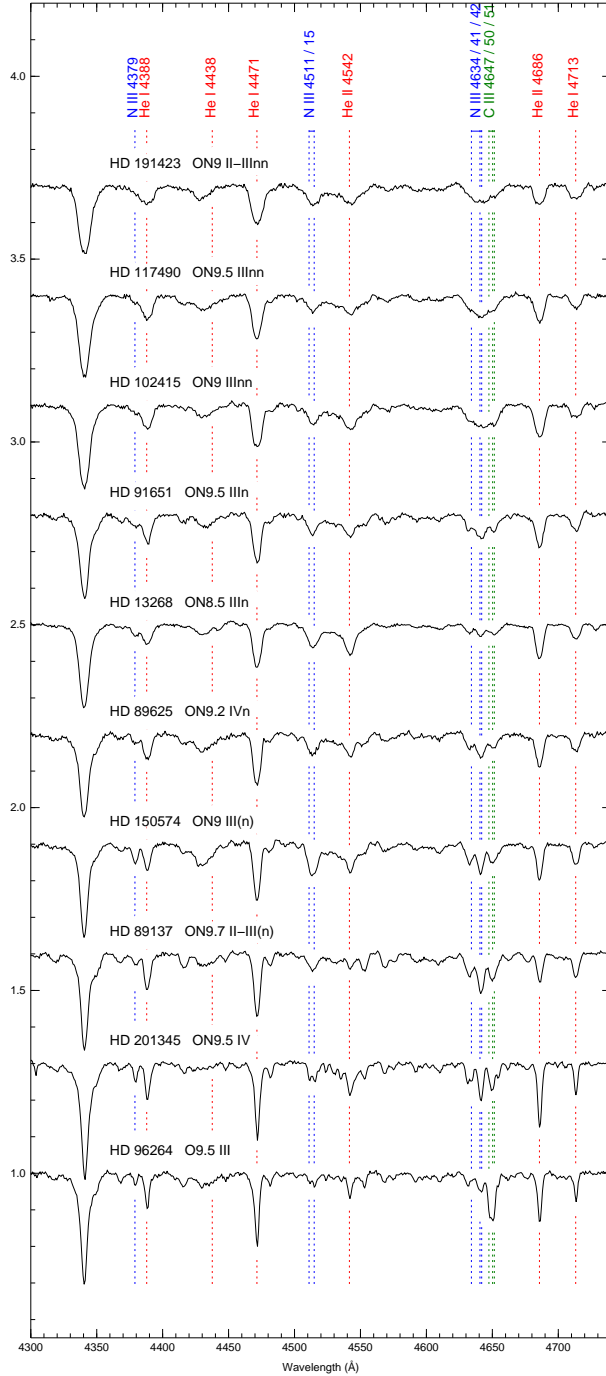


Fig. 2.— The spectra of the known ONn giants in order of increasing $v \sin i$ from bottom to top. This is Fig. 1 of Walborn et al. (2011) with the new example HD 89625 inserted. The restricted spectral range is intended to emphasize the behavior of the $\lambda\lambda 4640$ – 4650 blends. Below are the original ON star HD 201345 (Walborn 1970) with narrower lines, and the morphologically normal giant HD 96264 for contrast. Figure courtesy of Jesús Maíz Apellániz.

($\sim 300 \text{ km s}^{-1}$). This seamless interpolation again emphasizes the internal morphological consistency of the class, which likely corresponds to a uniform physical origin. Unfortunately, there are no quantitative spectroscopic data available for the little known HD 89625,¹ which is not even included in the OWN survey yet. For comparison with the values in Table 2 of Walborn et al. (2011), its Galactic latitude is -2.4° .

The mechanisms producing different degrees of processed material at the surfaces of OB stars are a subject of intense current debate. Most of the ONn spectra have recently been analyzed quantitatively and further discussed by Martins et al. (2015b). Perhaps the most vexing variable is the unobservable *initial* rotational velocity, which can be inferred only uncertainly and even somewhat circularly from evolutionary models. In the ONn class, however, the nitrogen enhancement is very likely related to the *current* rotational velocity. As discussed by Walborn et al. (2011) and Martins et al. (2015b), a high fraction of the class are spectroscopic binaries, and some are runaways, suggesting a mechanism involving binary evolution. This is an obvious problem ripe for intensive theoretical investigation with the hope of a well defined solution.

4. Discussion

4.1. Some Statistics

To date (January 2016) GOSSS has observed a total of nearly 900 O stars, for 590 of which reviewed or new spectral classifications have been or are about to be published (Sota et al. 2011, 2014; Maíz Apellániz et al. 2016, in press). The former total includes 56 with spectral types in the ranges O9–O9.7 Ib–Ia, of which 7 are ON and 4 OC; and 74 in the ranges O8.5–O9.7 IV–II(n)–nn, of which 8 are ON and none OC. Thus, the ON supergiants comprise 12.5% of the total in their spectral-type ranges, and the ONn giants 11% of their ranges. Of course, the “normal” samples exhibit differing degrees of mixed processed material, including nitrogen-strong (Nstr) and nitrogen-weak (Nwk) spectra that are less extreme than the ON/OC, and in particular a majority with some degree of mixing

¹This circumstance is likely related to the misclassification of B3/B4 (V) from the Michigan HD catalogue quoted (with a slight variation) by SIMBAD. A hypothesis for this error can be advanced: the weak, broadened He II lines were missed on the photographic objective-prism plate, while the difference between the He I spectrum and its maximum at type B2 was applied in the wrong direction. As reported in VizieR, B. Skiff (Catalogue of Stellar Spectral Classifications) has found that the original HD classification of B was upgraded to a relatively accurate B0 on the Extension chart.

among the supergiants (see Walborn 1976). The extreme ON/OC spectra are small tails of the overall distributions.

4.2. A New Classification Criterion for Somewhat Hotter ON I Spectra

As discussed early in the history of the OBN/OBC classification dichotomy (Walborn 1976), the recognition of such morphological anomalies is nonuniform in the HRD, depending upon the available features and their normal two-dimensional (temperature, luminosity) behavior. The $\lambda\lambda 4640\text{--}4650$ absorption blends in late-O supergiants provide a prime example. In normal spectra, the longward C III blend is much stronger than the adjacent, shortward N III. When the latter becomes the stronger in the rare ON spectra, a striking anomaly results (Fig. 1). When the two are about equal, the “Nstr” notation is used. However, this criterion functions optimally only in the restricted O9.2–B0.5 range. At later types, first the N III and then the C III become too weak and are dominated by O II blends at the same wavelengths. Toward earlier types, the issue is the progressive filling in of the N III absorption by the Of emission effect, such that it never exceeds the C III even for comparable or greater N enhancements. Thus, a strong selection effect in the ON classification arises. It is interesting to note that it also applies to the even rarer case of luminosity exceeding Ia, as in HDE 269896 with He II $\lambda 4686$ in emission despite the late-O spectral type; that has been compensated in its ON classification even though the N III absorption is only comparable to the C III.

Here we have introduced that same compensation for somewhat hotter supergiants, namely HDE 323110 and 328209, in which the two blends are again comparable, while other N III absorption features are abnormally intense and C III is deficient, as already described above. Actually, this development has recently been anticipated by the ON8 III((f)) classification of VFTS 819 in 30 Doradus (Walborn et al. 2014, Fig. 22) although $\lambda 4640$ is nearly neutral. Note that other N III absorption features in its spectrum, including $\lambda\lambda 4511\text{--}4515$, are stronger than in the somewhat more luminous O8 spectra adjacent to it in the figure.

The possible relevance of $\lambda\lambda 4511\text{--}4515$ as an additional indicator of N enhancement was discussed long ago by Bisiacchi et al. (1982). While their discrimination of the feature’s normal two-dimensional behavior was not entirely satisfying, their proposal deserves reconsideration in the present context. It would indeed be interesting if accurate quantitative EW measurements of this feature might reveal smaller, continuous degrees of N enhancement relative to the normal trends over a wider range of O types, as they discussed. Perhaps its ratio to C III $\lambda 4650$ would provide even higher sensitivity. As a start, we provide such measurements in Table 1 for the spectra in Figure 1. It is encouraging that the ratios show

monotonic discrimination among the ON, normal, and OC spectra in the expected sense: the ON range (which may well be real) runs from 0.83 to 2.35 with a mean of 1.48 ± 0.19 (m.e.), while the normal spectrum yields 0.4 and the OC 0.15. Those ratios can be derived from the measurements of Bisiacchi et al. for 8 supergiants with the classifications of which as such we agree (in a number of other cases they list as supergiants objects that are giants in our system; note also their typo for HD 202124): α Cam, 0.43; ζ Ori, 0.15; HD 75222, 0.19; μ Nor, 0.08; HD 152249, 0.10; HD 202124, 0.41; 19 Cep, 0.22; HD 225146, 0.10. Of these, ζ Ori is Nwk and HD 152249 is OC, while we consider the remainder to have morphologically normal CNO. Thus there is good to excellent agreement with our measurements in most cases, with the exceptions of μ Nor and HDE 225146, which have values appropriate for OC while their spectral appearance is compatible with normal CNO, albeit perhaps at the low-N side of the range. Bisiacchi et al. consider the full O-type spectral grid, not just the small range of this paper. Walborn et al. (2014, Figures 13 and 15) described the O6.5 V((f))z spectra of VFTS 089 and 761 as Nstr based on the unusual strength of $\lambda\lambda 4511\text{--}4515$ and other N III lines for that spectral type. Of course, these measurements should be undertaken in the extensive, full GOSSS sample to establish the normal trends and individual deviations from them. Such is beyond the scope of this study but shall be pursued in the future.

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